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The Environmental Design Space: Modeling and Performance Updates

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The Environmental Design Space (EDS) is a modeling and simulation environment devised for the design and evaluation of subsonic aircraft. One of the main features that sets it apart from other similar frameworks is its capability to perform aircraft performance and sizing, exhaust emissions, and noise prediction. These three elements are seamlessly executed due to the integration of multiple industry-standard tools. Since its conception in 2008, EDS has been used to support multiple research entities and projects for the evaluation of current and future aircraft concepts and technologies. Its results and assumptions have been calibrated and revised through the years in conjunction with panels of experts in the field. Therefore, it has undergone continuous development that has increased its capability, allowing it to model not only traditional tube-and-wing aircraft, but also unconventional configurations. At the writing of this paper, its capabilities extend beyond standard single and dual spool engines to include geared fans, ultra high bypass turbofans, open rotors, and partially turboelectric propulsion architectures. This paper presents an overview of how EDS has been used to support major research efforts. Then, an approach to develop and calibrate engine and aircraft models to match existing open-source data is presented. Finally, a summary of available advanced engine and aircraft architectures is shown. The results demonstrate EDS capability to create models that closely match existing systems performance, and its flexibility to keep supporting future aircraft design and technology development studies.

Nomenclature

ANOPP	=	Aircraft Noise Prediction Program
BPR	=	bypass ratio
CMPGEN	=	Compressor Map Generation
FAR	=	fuel air ratio
GW	=	aircraft gross weight
MTOW	=	max takeoff weight
NPD	=	Noise Power Distance
NPSS	=	Numerical Propulsion System Simulation
OPR	=	overall pressure ratio
SAR	=	specific air range
SW	=	wing area
TSFC	=	thrust specific fuel consumption
TWR	=	design thrust to weight ratio
WATE	=	Weight Approximation for Turbine Engines
WSR	=	design wing loading

I. Introduction

THE Environmental Design Space (EDS) is a multidisciplinary, physics-based, modeling and simulation environment for subsonic aircraft design. Motivated by the increased environmental impacts of aviation, EDS was conceived with

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the goal of being able to capture the complex interrelationships between emissions and noise, to support technology evaluation studies, and to perform gap analysis. Its development was performed by Georgia Tech's Aerospace Systems Design Laboratory (ASDL) and reviewed by an Independent Review Group of both government and industrial entities. It was first documented during the ICAS congress of 2008 by Kirby [1] and Barros [2]. In general terms, EDS consists of a comprehensive set of tools capable of producing performance, emissions, and noise prediction. These are arranged in the execution sequence shown in Fig. 1, color-coded to denote the tools used at each step. Integration between tools is performed using NPSS object-oriented programming language. This ensures a seamless data flow between analyses without requiring any user intervention. the following are the tools and methods used in EDS:

- CMPGEN: off-design axial compressor map generation [3]
- NPSS: engine cycle design and simulation [4, 5]
- WATE: engine flowpath and weight estimation [6]
- FLOPS: aircraft sizing and performance [7]
- P3T3: emissions empirical correlations [8]
- ANOPP: engine and airframe noise analysis [9]
- AEDT Tester: reduced version of FAA's Aviation Environmental Design Tool (AEDT) [10]

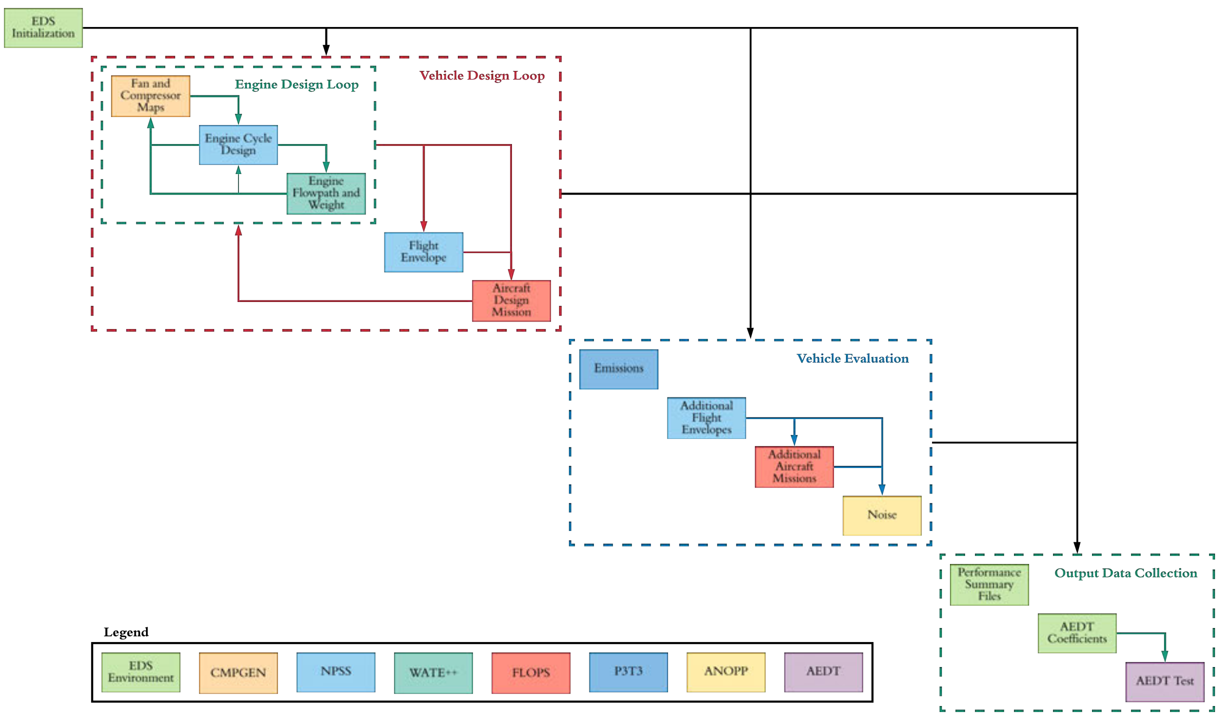

Fig. 1 Environmental Design Space Overview

Since its creation, EDS has been used to support a wide variety of research projects, which are reviewed in Sec. II. Therefore, it has been going through continuous development throughout the years. It is the goal of this paper to provide an update to the research community on the state of EDS and to document the evolution of its capabilities. For that purpose, this paper will focus on the engine design and aircraft analysis portion of EDS, whereas noise and emissions will be treated separately on a subsequent publication. The approach used to design propulsion systems and develop notional models of existing engines is presented in Sec. III. Section IV illustrates how EDS is used to model conventional tube-and-wing vehicles representative of each class of current aircraft in service. Finally Sec. V shows the development of advanced propulsive architectures (including turbo-electric systems), as well as unconventional configurations such as Hybrid-Wing Body (HWB), and Truss-Braced Wings (TBW).

II. History of Development and Survey of Work

A. EDS Conception

The development of the Environmental Design Space formally began in 2005 as a response to the recommendations from the 2004 Committee on Aviation Environmental Protection (CAEP) meeting. There, it was recognized the need to develop a comprehensive set of tools that would allow quantifying the environmental impacts of aviation. These impacts needed to be assessed not only for current but also future aircraft systems. The goal was to develop the modeling capability to predict what the environmental footprint of future aircraft fleets could be. This tool would support decision makers in evaluating different technology development scenarios, providing them with additional information to make informed decisions related to establishing goals and potential investment strategies.

At the time, the Federal Aviation Administration (FAA) had a goal to develop a set of independent aviation analysis tools that were capable of quantifying some of these elements (noise, performance, emissions, etc.) individually. A need was identified to develop a common modeling environment that could integrate these tools together. This led to the conception of EDS at the Georgia Institute of Technology through the *"Partnership for AiR Transportation Noise and Emissions Reduction"* (PARTNER) Center of Excellence. Since its development, the design philosophy behind EDS was to utilize non-proprietary, physics-based methods to facilitate sharing information with independent expert review groups. The first set of publications that documented the development of EDS were published during the ICAS congress of 2008. Kirby [1] described the development of the tool and its general structure, whereas the Barros [2] outlined a framework for the calibration and verification of the EDS aircraft models, and how the environment could be used to perform technology assessments and trade space analysis.

B. Initial Studies: Demonstration of EDS Capabilities

Since its creation, EDS has been used to support global stakeholders in the development of certification standards and new technology assessments. Given its capabilities, it has been used to support the CAEP working group in the development of Standard and Recommended Practices (SARPs), such as Landing and Take-off (LTO) cycle NOx emissions, certification noise, and CO_2 standards. Kirby [11] describes how these standards have evolved since the first CAEP meeting (CAEP/1), and how EDS has been used to support decision makers during these exercises. Specifically, EDS was used to model the required improvements in combustor and engine technology necessary to meet various levels of NOx reductions targets in two notional vehicle models. This analysis covered from simple modifications on the combustor models to a complete re-design of the engine and its thermodynamic cycle. This study revealed strong interdependencies between emissions and fuel burn.

The aforementioned study did not model the impact of a specific technology. Instead, it performed a gap analysis to determine the necessary improvements in current system performance in order to achieve a certain goal. Using the EDS framework, Georgia Tech researchers supported the PARTNER Center of Excellence in the development of CO_2 certification standards which target, as an ultimate goal, the improvement of aircraft's fuel efficiency standards. As reported in Ref. [12], aircraft and engine efficiency are not strongly correlated. This motivated the need to develop an aircraft-level emissions certification standard that went beyond engine-focused certification metrics such as the Dp/Foo index. In this context, EDS capabilities became paramount to capture these relationships. The study led to the conclusion that metrics such as block fuel and 1/Specific Air Range (1/SAR) were more appropriate to be used for certification purposes when correlated against MTOW.

Another important feature behind EDS is its capability to interface with other tools to perform fleet-level analysis. For instance, Ref. [13] demonstrated how EDS could be used to support the assessment of new vehicle concepts and operations on Next Generation Air Transportation System (NextGen), such as cruise-efficient Short Takeoff and Landing (STOL) transports and supersonic aircraft. On the same subject, Refs. [10, 14] presented an approach in which surrogate modeling techniques could be used to employ EDS-generated vehicle models to perform fleet-level analyses. That work also documented how EDS was configured to produce the necessary data to interface with FAA's AEDT tool. This included the development of parametric correction factors to represent an entire aircraft fleet by using a single aircraft performance model for each vehicle class.

Last but not least, LeVine [15] provided an overview of the sensitivity of noise metrics with respect to high-level design parameters used in EDS. As shown in Fig. 1, ANOPP is the program used for noise prediction. This tool is integrated in the EDS framework and executed during the vehicle evaluation loop, requiring a fully converged engine and vehicle model. In his work, LeVine used Design of Experiment (DOE) techniques to sample a multi-dimensional design space and determine the impact of high level design variables (wing area, engine cycle, etc) into Noise-Power

Distance (NPD) curves, Effective Perceived Noise Level (EPNL), and Sound Exposure Level (SEL). The trends revealed in this study provided a better understanding of cumulative noise metrics such as Day-Night Sound Level (DNL), which are used for establishing certification standards.

C. Advanced Engine, Aircraft, and Technology Assessments

The previous review, while not fully comprehensive, provided a demonstration of EDS capabilities in its three main fronts: aircraft design and performance, emission assessments, and noise predictions. It is important to note that, although not directly referenced in this paper, this early EDS work was a cornerstone in PhD dissertations such as those by De Luis [16] and Becker [17]. Now the focus shifts towards how EDS has been used to assess sets of future technology portfolios and their potential impacts on aircraft performance. This kind of work has increased EDS's capability to model unconventional propulsion and airframe systems. This section focuses on the work performed under the Continuous Lower Energy, Emissions, and Noise (CLEEN) Program (Phases I and II), NASA's Environmental Responsible Aviation (ERA) [18], Subsonic Fixed Wing (FW) [19], and Advanced Air Transport Technology (AATT) [20] projects.

CLEEN is an FAA's program that aims to develop technologies that reduce emissions, noise, and fuel consumption, while exploring their potential integration into current and future aircraft [21]. The first phase of this project started in 2010, and consisted of a five year effort between multiple companies such as Boeing, General Electric, Honeywell, Pratt & Whitney, and Rolls-Royce. ASDL used EDS to support this FAA program through the PARTNER Center of Excellence Project 36 [22]. This effort leveraged generic vehicle baselines developed during previous projects. Then, CLEEN-funded technologies were modeled in each vehicle class to provide an independent assessment of their potential benefits. The focus of such analysis was on fuel burn, emissions, and noise at both the system (under proprietary arrangement) and the fleet levels. This program resulted in a follow up project, CLEEN Phase II, launched in 2015 and supported through PARTNER Project 37 [23], in which EDS continued to be the tool used for both systems and fleet analyses.

One key contribution from EDS was the development of a Multi-Design Point (MDP) methodology for engine cycle design, which was initially conceived during Schutte's PhD thesis [24], and a paper on the MDP implementation in EDS was later published in Reference [25]. It is important to note that even though MDP methods are common in industry, this was the first instance of one of such methods being openly documented and published. This MDP method was key in the assessment of advanced aircraft and engine concepts during both the NASA ERA and FW projects. In these projects, unconventional aircraft such as Hybrid-Wing Bodies (HWB), Truss-Braced Wings (TBW), and Box-Wing (BW) were modeled, providing a significant leap from traditional T&W vehicles. Additionally, advanced engine architectures such as Open-Rotors, Ultra High Bypass Ratio, Advanced Direct Drive (ADD), and Geared Fans (GF) were also developed. More details about the modeling approach employed is presented in Sec. V.

References [26, 27] provide a description of how EDS was used to address the goals of the ERA project. This series of papers provided initial predictions of potential fuel, emissions, and noise reductions for different combinations of the ERA technology portfolio, serving as a demonstration of EDS' capability of performing these kind of interdisciplinary studies. Under the same effort, Kestner [28] presented an approach for optimal engine cycle selection using surrogate models to facilitate design space exploration and performance trade studies. This work demonstrated the suitability and computationally efficiency of employing surrogate models as a viable alternative to evaluate multiple technology portfolios, especially considering the challenge that optimal cycles might vary depending on the type of technologies applied. EDS was used as the modeling and simulation environment for these assessments, providing a platform to examine engine performance trends and to understand the impact of design decisions for the midterm timeframe.

In a follow-up work, Kestner used EDS and the surrogate-based engine cycle selection methodology to analyze performance changes in both engine and aircraft for five different scenarios: regular gas turbine evolution, midterm airframe and engine technologies, and midterm technologies but on a HWB aircraft with either podded engines or with Boundary Layer Ingestion (BLI) [29]. The results from these analyses illustrated a set of Pareto frontiers between fuel burn, emissions, and noise, showing how optimal cycle selection changed across different scenarios and under different sets of performance constraints. Under the same effort, EDS was employed to assess the impacts of core engine technologies against other propulsor engine technologies with the goal of estimating potential fuel burn benefits and assist decision makers in determining technology development roadmaps [30].

In this field of analyzing advanced propulsion systems, EDS modeling methodology has been continuously revised and scrutinized by different sets of expert panels. Guynn [31], for example, performed an engine study to determine the impact of two different propulsion architectures (direct drive vs geared fan) in notional advanced aircraft concepts. In this report, Guynn states that technology curves for fan and compressor design tip speeds and efficiencies were taken from those used in EDS. These technology trends were also used by Felder [32] in the analysis of the TeDP concept.

EDS has also been used as the simulation environment to perform assessments of different technology portfolios, enabling stakeholders to quantify potential impacts and show their benefits at the vehicle and fleet level [33]. Jimenez [34], for example, employed EDS for the development of vehicle performance models that were later used in fleet-level assessments to estimate the impact of introducing new aircraft systems, featuring new technologies, would have on an entire airline concept of operations. Busch [35] used EDS to perform uncertainty analyses on a notional HWB concept representative of NASA's N3-X electric aircraft. The software's flexibility was leveraged to quantify the sensitivity of this concept's performance (fuel burn and noise) with respect to the assumed technology levels. As a result, technologies critical to realize the concepts benefits were identified.

For the past years, EDS has been used to support NASA's AATT project, in which parametric models were developed for five classes of vehicles for both ADD and GTF engine architectures and for the midterm and far-term time frames. In order to capture technologies in the far-term time frame, additional capabilities were added to model advanced propulsion architectures and airframes. An example of advanced propulsion architecture is hybrid electric propulsion as shown in Sec. V.B, and an example of advanced airframe is a parametric representations of Truss-Braced Wing (TBW) aircraft.

D. Current Work

EDS continues to play a key role in supporting ASDL research portfolio. Recently, it was used as the modeling environment during the Independent Expert Integrated Review (IEIR) study, funded by the FAA through the ASCENT Center of Excellence. The final report, published in 2019 [36], documented the usage of EDS as the modeling environment in the analysis of three different technology scenarios: TS1, continuation of current trends, TS2, "increased pressure", and TS3 "further increased pressure" and their subsequent impacts on fuel burn, emissions, and noise for future aircraft in four seat classes: Business Jet (<20), Regional Jet (20–100), Single Aisle (101–210), and Twin Aisle (211–300). These analyses were projected to define performance improvement goals for the 2027 and 2037 time frames.

Under ASCENT Project 43, EDS has been supporting a re-evaluation of NPD curve generation procedures. Sensitivity analyses have been used to correlate aircraft design features and mission operations to community noise metrics [37]. It is also used to assess the potential impacts that high performance fuels could have on existing and future aircraft on a research effort funded by the Department of Energy.

Finally, organizations such as the International Civil Aviation Organization (ICAO), the Air Transport Action Group (ATAG), among others, have pushed for the establishment of long-term goals for aviation as a global industry to significantly reduce its environmental impact. In specific, a target has been set for aviation to reduce net emissions by 50% by the year 2050 [38]. This new effort by ICAO has been themed as the "Long Term Aspirational Goals" (LTAG) for international aviation, in which ASDL is participating. One of its goals will be to identify, characterize, classify, and evaluate technologies, systems, and operational measures with the potential to reduce CO_2 emissions. EDS will be used as the modeling environment for the analysis of the impact that such technologies could have on aircraft performance. It is expected that, during this research effort, EDS undergoes additional development, especially considering the aggressiveness of this target, in which hydrogen-powered aviation has been identified as a potential enabler to achieve these goals [39].

III. Engine Design and Calibration in EDS

The first part of a regular EDS execution is the *Engine Design Loop*. This process consists of three main elements: fan and compressor map generation, aerothermodynamic cycle, and flowpath design. For these, CMPGEN, NPSS, and WATE++ are linked together in an iterative process to ensure agreement between the three. The result of this loop is a tabular set of engine performance data (an engine deck), dimensions, and weight, that are then passed over to the *Vehicle Design Loop* (see Fig. 1). This section first presents an overview of the *Engine Design Loop*, and then describes the process used to develop engine models to represent the performance of existing engines in service.

A. Engine Design Loop Overview

CMPGEN is a modeling tool developed by GE for NASA used for the generation of component performance maps for axial fans and compressors. These maps consists 4D tables that contain information in regards to pressure ratios, corrected flow, % corrected speed, and adiabatic efficiency, which are compatible with NPSS to be used during off-design performance evaluations. In EDS, CMPGEN is the first element executed during the Engine Design Loop. It is used to estimate off-design characteristics of fan and compressor elements as a function design pressure ratios, specific flows, tip speeds, and other high level design parameters.

The Numerical Propulsion System Simulation (NPSS) is the software used for engine cycle design. A Multi-Design Point (MDP) process is employed in NPSS for the design of the engine thermodynamic cycle. In this process, different sizing points are considered simultaneously in on-design mode, which ensures that the resulting engine is capable of meeting performance targets and constraints at different conditions [25]. Five design points are used in this MDP evaluation:

- **Aero Design Point (ADP):** reference point used for turbomachinery performance.
- **Top of Climb (TOC):** target thrust point, established by airframe requirements. This sets the maximum mass flow and corrected speed.
- **Takeoff (TO):** target thrust point, at which max temperature levels are established for high bypass ratio engines.
- **Sea-level Static (SLS) Installed:** constraint point to ensure that flat rated target thrust can be achieved, as well as max temperature limits are not exceeded.
- **SLS Uninstalled:** point used to set the maximum SLS thrust. It is at this point that information about the engine model is also used to perform calibrations with respect to ICAO test performance data [40].

This MDP process is a considerable improvement with respect to traditional Single-Design Point (SDP) strategies, where these performance constraints are instead verified during the off-design operation of the engine model. After this MDP process has converged, the engine is sampled at different flight conditions to determine the flow states at some critical conditions which drive the mechanical design, such as maximum temperatures or stress levels. Using this information, WATE++ is used to perform the mechanical design, engine component sizing, and weight estimation.

In EDS, a single model file is used to define all the potential elements to be included in a propulsion architecture. This eliminates the need of having to create separate models for each. Instead, a high-level model definition file can be used to define which elements are included on a given engine, in conjunction with a file that lists the design variables (pressure ratios, for example) for a particular model. In this way, flexibility is added to model not only a common two-spool turbofan system (as represented in Fig. 2), but also three-spool systems (see Sec. V.A), turbo-electric architectures (Sec. V.B), and among others.

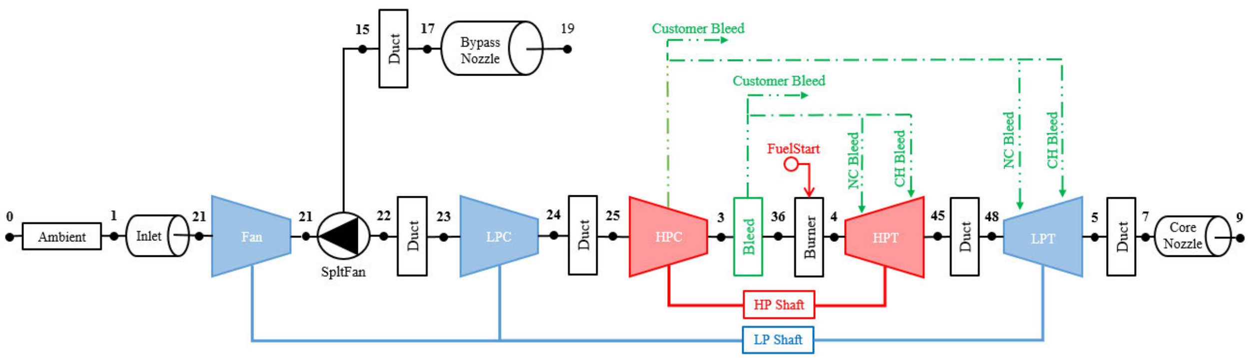

Fig. 2 Schematic of Notional 2-Spool Engine Architecture

B. Engine Model Development and Calibration

The most challenging aspect of simulating an existing engine model is that few performance data is publicly available. Engine manufacturer's websites can be used to obtain a notion of high-level parameters such as fan diameters, turbomachinery arrangements, and some ranges for rated thrust, pressure ratios, and bypass ratios. Therefore, the approach used is to rely on the ICAO engine database [40] as a source to obtain both NOx emission and sea-level static (uninstalled) performance data, such as Max Rated Thrust, Overall Pressure Ratio (OPR), Bypass Ratio (BPR), and fuel flows for four different thrust settings (takeoff, climb-out, approach, and idle). Note that ICAO engine database labels sea-level static thrust as takeoff. Using the MDP process, the user iterates on engine design parameters to match published performance data. Additionally, the EDS models are also calibrated to match the fan diameter and the number of stages of each turbomachinery component.

To illustrate the results obtained during this calibration process, Table 1 shows a comparison between ICAO data and the available engine model in EDS for the CFM56-7B27 and GE90-94B engines. This demonstrates the good agreement between the EDS model with respect to engine performance data reported in the ICAO Databank. Similarly, Fig. 3 shows the off-design performance summarized in the form of TSFC vs Thrust curves.

Table 1 Comparison of ICAO Data vs EDS Engine Models

		CFM56-7B27		**GE90-94B**	
Variable	Units	ICAO	EDS	ICAO	EDS
Rated Thrust	KN	121.44	121.44	432.8	432.8
BPR	-	5.00	5.00	8.33	8.32
OPR	-	28.63	28.63	40.53	40.55
Fuel Flow (TO)[1]	kg/s	1.284	1.276	3.514	3.464
Fuel Flow (C/O)[2]	kg/s	1.043	1.045	2.848	2.839
Fuel Flow (AP)[3]	kg/s	0.349	0.345	0.908	0.909
Fuel Flow (ID)[4]	kg/s	0.116	0.117	0.296	0.269

[1] Takeoff, 100% of max rated thrust
[2] Climb out, 85% of max rated thrust
[3] Approach, 30% of max rated thrust
[4] Idle, 7% of max rated thrust

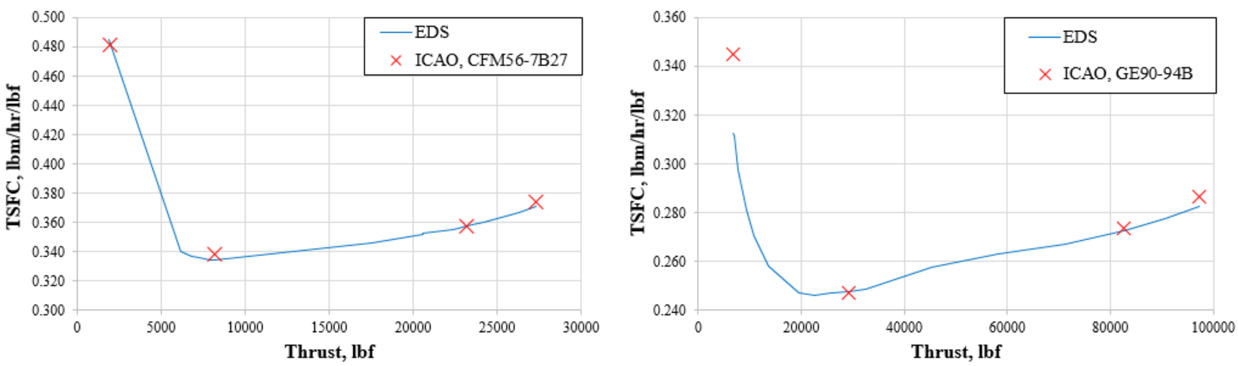

Fig. 3 CFM56-7B (Left) and GE90-94B (Right) TSFC vs Thrust at Sea Level Static Conditions

It is important to note that often engine manufacturers produce different thrust variants of the same engine in order to better service the needs of an specific aircraft. In such cases, it is not necessary to produce a new engine model for each engine variant. Instead, the approach employed is to match the performance of the highest rated thrust engine in each series, and then use a *rating* variable to adjust the rated thrust level for each engine. For instance, Fig. 4 shows TSFC vs Thrust curves for three variants of the CFM56-7B and PW1500G engine series. Also shown is the calibrated model in EDS for the max rated thrust engine in this series.

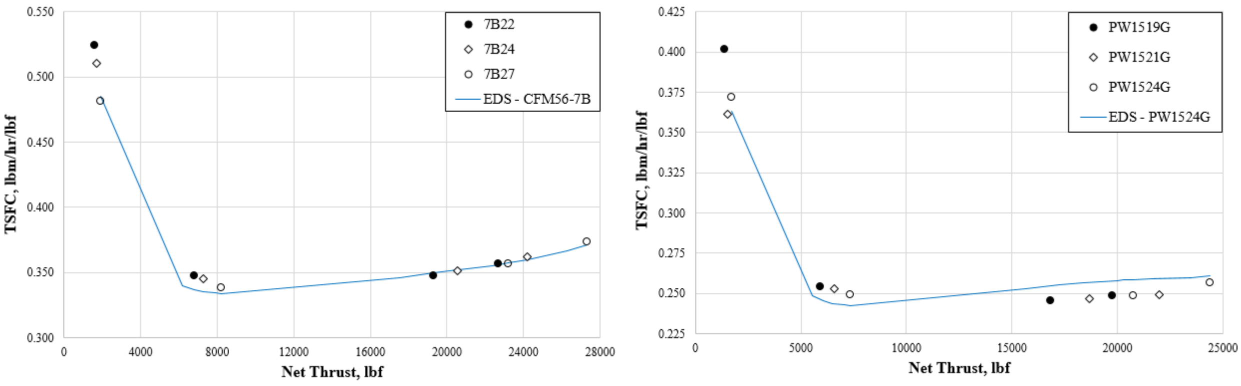

Fig. 4 CFM56-7B (Left) and PW1500G (Right) Engine Series

Using the approach outlined above, other notional engine models have been developed, such as the the CF34-8C5, CF6-80C2, and PW4056. These are used in the baseline aircraft models shown in the next section.

IV. Development and Calibration of Baseline Vehicle References

One of the overarching goals of EDS is to perform assessments of different subsonic aircraft variants and potential future systems. In order to obtain representative models of current aircraft in use, these have been classified into different classes given their seat capacity (50–400+ passengers) and cabin arrangements (single-aisle, twin-aisle) [41]. Then, for each class, a representative-in-class aircraft model has been developed and acts as the reference datum from which new systems are compared to. This section describes the vehicle design loop employed by EDS and the process employed to develop these baseline aircraft. Finally, a brief description is provided on the development of additional models that represent current technology levels for some aircraft classes.

A. Vehicle Design Loop

EDS makes use of NASA's Flight Optimization System (FLOPS) to size the aircraft, estimate aircraft drag polars and component weights, and perform mission analysis. This Fortran-based code is able to perform these calculations in less than a fraction of a second, which makes it appropriate to perform design space exploration studies. In EDS, FLOPS is executed right after the engine design loop has finished and successfully converged. This engine loop results in an engine deck, basic nacelle dimensions (length and diameter) and weight. In addition from these engine inputs, FLOPS also requires aircraft geometry and a mission description (design range, Mach numbers, altitudes, etc.). Options are also available to provide more detailed landing and takeoff data, as well as performance constraints to be enforced.

For now, the focus is on the way the vehicle design loop is executed. FLOPS is given an initial guess for gross weight, as well as the vehicle geometry information, and it estimates weight of internal components, such as fuselage, wing, tail, etc. This yields an operating empty weight (OEW). The maximum available fuel capacity is found by subtracting OEW and payload weight from gross weight (GW). With this fuel capacity, FLOPS then "flies" the mission, and determines the max allowable range with this fuel available. FLOPS iterates on GW until the mission range matches the input design range. After this internal sizing loop converges, a set of performance constraints are verified to determine on whether the engine has to be re-sized, which would return EDS back to its engine design loop, or otherwise proceeds to the vehicle evaluation loop, where emissions and noise assessments are performed.

B. Aircraft Model Development and Calibration

Similarly to the approach used in developing and calibrating engine models, as shown in Sec. III.B, it is desired to use publicly available data when developing an aircraft model to be used in EDS. The approach is to use data available in the *Airplane Characteristics for Airport Planning* (ARPD) documents, provided by each airframe manufacturer (see Refs. [42, 43]). These provide data such as geometry (wing areas, fuselage lengths, tail aspect ratios, etc.), major aircraft weight breakdown (i.e. maximum take-off weight, empty weight, zero fuel weights, etc.), payload (i.e. number of passengers), cabin arrangements, and payload-range performance envelopes.

Note that ARPDs often provide data for different variants of the same aircraft. These include but are not limited to seat arrangements, weight options, and engines used. For example, the ARPD for the Boeing 747-400 contains different payload-range diagrams for three engine variants: CF6-80C2B1F, RB211-524G, and PW4056 engines. These diagrams also come with their own set of embedded assumptions, such as assumed weight per passenger, design cruise Mach number, among others. Another major configuration difference consists of the different weight variants for the same airframe. Table 2 shows, for example, a summary of the three weight variants presented by Boeing's 737 ARPD document for the 737-800 aircraft.

Table 2 Boeing 737-800 Component Weight Summary (Adapted from [44])

Component	Model 737-800 Variants		
Max Design Ramp Weight	156,000	173,000	174,900
Max Design Takeoff Weight	155,500	172,500	174,200
Max Landing Weight	144,000	144,000	146,300
Max Zero Fuel Weight	136,000	136,000	138,300
Operating Empty Weight	91,300	91,300	91,300

To recap, three pieces of information are taken from ARPDs: 1) geometric characteristics and cabin arrangement, 2) major aircraft weight breakdown, and 3) aircraft's payload-range diagram. The process of selecting a sizing point and calibrating the aircraft model requires considering these three pieces of information simultaneously to ensure consistency. FLOPS internal weight [45] and aerodynamic estimation techniques [46] are used to size and calibrate the vehicle.

Using this process, a set of six vehicles were modeled, which act as the representative-in-class vehicles for each class. Table 3 presented here contains a high level summary of these baseline aircraft. These are notional representations of existing systems, for which FAA's classification convention has been used:

- RJ: Regional Jet
- SSA / LSA : Short Single Aisle / Large Single Aisle
- STA / LTA : Short Twin Aisle / Large Twin Aisle
- VLV : Very Large Vehicle

Table 3 Baseline Airframes Sizing and Performance Data

Reference Aircraft for Each Class						
Vehicle	RJ	SSA	LSA	STA	LTA	VLV
Seat Class	50–99	100–149	150–199	200–299	300–399	400+
Notional Engine	CF34-8C5A3	CFM56-7B22	CFM56-7B27	CF6-80C2B5F	GE90-94B	PW4056
Mission and Sizing Data						
Thrust (lbf)[1]	14,507	22,699	27,300	61,243	97,258	56,742
Wing Area (ft^2)	752	1,409	1,409	3,200	4,927	6,203
Range (nmi)	1880	3,240	2,855	5,920	7,550	7,175
Fuel (US gal)[2]	2,827	6,734	6,992	23,843	37,500	58,328
Major Group Weights Summary (lbf)						
MRW	85,000	155,000	174,900	413,000	634,500	873,000
OEW	48,000	83,000	91,300	198,440	304,500	394,000
PAYLOAD	18,060	26,880	36,750	54,810	78,750	88,200

[1] Max rated thrust per engine at sea level static conditions
[2] Assumed fuel density = 6.77 lbf/US gal

C. Additional Available Vehicles

In addition to the baseline aircraft described above, a set of "new-in-class" airframes has been modeled in EDS for some vehicle classes. These are notional representations of existing aircraft with the purpose of having a model that resembles the performance of such system. The process to obtain these systems was identical to the process outlined above, with the only exception being the notional A350XWB model which required a new engine architecture. This subject is treated separately in Sec. V.A. The following list shows some of these additional models that have been developed and calibrated.

1) Notional G650ER (< 20 passengers)
2) Notional Embraer E190-E2 (100–149 passengers)
3) Notional Boeing 737-8 and A320neo (150–199 passengers)
4) Notional A350XWB (300–399 passengers)

V. Modeling and Development of Advanced Engines and Airframes

The previous sections discussed the approach used to develop engine and aircraft models for rather "conventional" vehicles. This section starts off by discussing the approach used to model a 3-spool engine architecture such as the Trent XWB-84 engine used in the A350XWB. Then, individual sections are dedicated to the capability of EDS to simulate propulsion architectures that feature electric components, as well as non-conventional airframes such as Truss-braced wings, hybrid-wing bodies, among others. These represent a significant improvement in EDS simulation capability and showcase its flexibility.

A. 3-spool System: Notional A350XWB

Looking at the newest technology developments and trends in engine performance, there is a strong push towards achieving high bypass ratio engines to yield higher propulsive efficiency. This push has led to the development of geared fan architecture in order to decouple fan speed with respect to the low pressure shaft speed, allowing to operate both the fan and the low-pressure turbine closer to their optimal efficiency. Another strong technology push consists of the transition towards More-Electric Aircraft (MEA) and bleed-less systems such as the Boeing 787. The latter employs Rolls Royce Trent 1000 engine, where all the power for subsystems is extracted from the intermediate pressure shaft.

Recognizing these trends, it became necessary to have the modeling capability for three-spool propulsion systems, on top of the standard two-spool engine shown in Fig. 2. This required the inclusion of an intermediate pressure turbine in the baseline engine model definition file, with its subsequent shaft and bleed linkports, and an additional set of solver dep/indep pairs to properly handle the changes to the MDP analysis logic of this new architecture. The developed model followed the same calibration process outlined in Sec. III and was calibrated to resemble the performance of Rolls Royce's Trent XWB-84 engine. Figure 5 shows the close agreement of the developed EDS engine model with respect to data contained in the ICAO data bank.

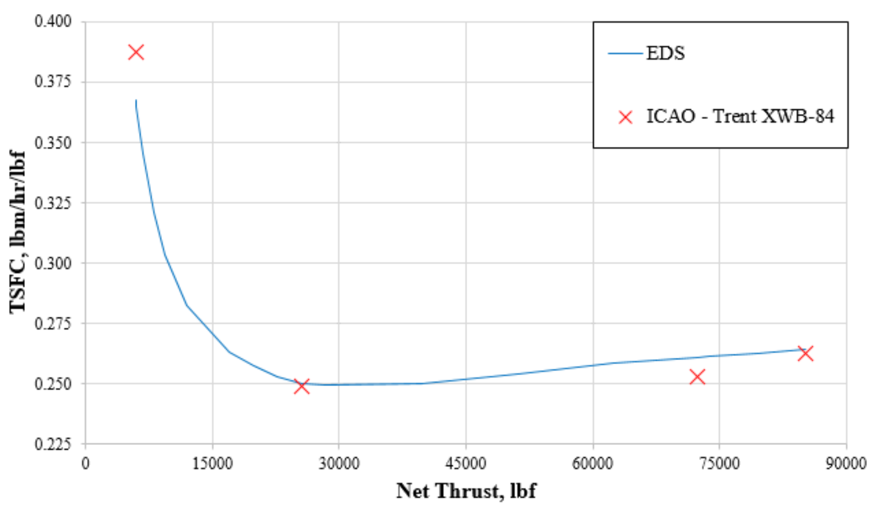

Fig. 5 Comparison of EDS Engine Model vs ICAO Data for the Rolls Royce Trent XWB-84

Finally, this engine model was included into a notional representation of the A350XWB aircraft. This model is representative of what would be a new-in-class for the 300–399 pax class. As shown in Sec. IV, an ARPD was used to obtain the weight, geometric, and mission to calibrate this vehicle model.

B. Partially Turboelectric System: Notional STARC-ABL

The STARC-ABL is an advanced aircraft concept initially proposed by Welstead and Felder from NASA in 2016 [47]. It consists of a tube-and-wing aircraft with dimensions similar to a 737-800 but with a partially turboelectric propulsion architecture. In this arrangement, power is extracted from two underwing turbofan engines to power an electric fan mounted in the tailcone of the fuselage that ingests boundary layer flow. This concept has gained attention over the past years given its relatively simple configuration with respect to other unconventional concepts such as hybrid-wing bodies or truss-braced wings.

At ASDL, capability to model hybrid and turboelectric propulsion architectures was normally performed using another tool known as GT-HEAT [48]. This tool uses NPSS for engine design by leveraging a set of custom NPSS elements to model electric components [49]. Furthermore, NPSS is also used to perform mission analysis, resulting in a tightly integrated environment that performs "real time" mission analysis and engine design. GT-HEAT, however, lacks the ability to model emissions and noise as EDS. Therefore, it was decided to port over some of this capability over to EDS. This work was documented by Brucculeri [50], who also implemented a 1D optimizer for power management control between the turbofans and the BLI electric fan. The result is a common modeling environment that allows performing direct performance comparisons between an unconventional advanced propulsion architecture such as the STARC-ABL with respect to the baseline vehicles currently available in EDS. This eliminates the potential source of uncertainty of having these two vehicles being modeled in different simulation environments. Future work is planned to keep modeling more variants of these advanced propulsion systems including but not limited to fully turboelectric and hybrid electric systems.

C. High Aspect Ratio Truss-Braced Wing Vehicle

Starting from basic aircraft performance principles, it is well known that wings with higher aspect ratio have lower induced drag and higher lift-to-drag ratios, a desirable feature to reduce mission fuel consumption. However, as a wing aspect ratio increases, it becomes necessary to employ a more resistant structure and materials in order to withstand the aerodynamic and inertial loads since the wing is basically a long slender cantilever beam. This yields a physical limit to the point at which aspect ratio can be increased before it becomes detrimental to performance as structural weight becomes prohibitively high. Under these considerations, the concept of a Truss-Braced Wing (TBW) has been conceived as a potential configuration to enable such High Aspect Ratio Wing (HARW) configurations. These have been subject of extensive research over the past few years. The development and design space exploration of baseline TBW aircraft is fully documented in NASA's 2015 Contractor Report in Ref. [51].

However, modeling a HARW in EDS proposes two fundamental challenges: 1) wing weight estimation, and 2) aerodynamic drag polar calculations. For conventional airframes, EDS relies on FLOPS for weight calculations (full details can be found on Ref. [45]), as well as its internal aerodynamic estimation routines (based on the Empirical Drag Estimation Technique, EDET) for the calculation of drag polars to be used in mission analysis and performance. In the past, as a result of a joint effort between Virginia Tech and Georgia Tech, high-fidelity CFD and aeroelastic simulations were performed to obtain surrogate models that calculate aerodynamic coefficients (C_{D_0}, C_{D_i}) and wing weight for three classes of vehicles: regional jet (50–100pax), large single aisle (150–200pax), and short twin aisle (200–299pax). These surrogate models were created as a function of high-level design parameters such as wing area, aspect ratio, sweep angle, among others.

Currently, EDS contains a model of a TBW aircraft calibrated to match the geometry, weight, and performance of the "765-095 Rev D" configuration presented in the SUGAR 2015 report [51]. For this model, high-fidelity aeroelastic simulations were performed using the Rapid Airframe Design Environment (RADE) [52], which presents an evolution with respect to the surrogate models inherited from the GT/VT study referenced before. These new surrogate models calculate wing weight for a series of wing aspect ratios, wing area, and takeoff gross weight, allowing to perform design space exploration studies for aspect ratios from 16 to 22. In addition, a custom-made aerodynamic estimation technique has been created that re-uses some of the EDET drag routines, but allows for the integration of CFD data for specific components and flight conditions.

D. Other Unconventional Configurations and Airframes

On the engine side, EDS has been used to develop notional models of advanced propulsion systems such as Advanced Direct Drive (ADD) High Bypass Ratio turbofans, Geared Fan Turbofan (GTF), Ultra High Bypass Turbofan [29] with Variable Pitch Fan (VPF) or Variable Area Nozzles (VAN) [53], and Open Rotor engine architectures [54–56]. As for unconventional aircraft, work has been done to model hybrid wing body (HWB), box-wing aircraft (BW), over-the-wing nacelle (OWN), among others. These were developed as part of NASA's ERA and FW projects (See Sec. II). All of these have been modeled under a common framework, which facilitates performing comparisons across concepts.

VI. Conclusion

The Environmental Design Space (EDS) is a modeling and simulation environment devised for the design and evaluation of subsonic aircraft. In general terms, EDS consists of a comprehensive set of tools capable of engine design, aircraft sizing and performance analyses, emission estimations, and noise prediction. Its main strengths rely on the seamless integration of different industry-standard analysis tool under a single framework, the unification of both conventional and unconventional propulsion and aircraft systems, and the continuous revision and validation that it has been subject to. This paper started with providing an overview of its capabilities, as well as the major milestones of its development history. This survey, although not fully comprehensive, still provides a wide coverage of some of the most important projects that have been supported by EDS. Besides, it continuously supports numerous graduate students while conducting their Master and PhD theses, each one of those often adding additional capabilities to it or serving as another demonstration of its capabilities. In addition, this paper also presented an approach to develop and calibrate engine and aircraft models based on publicly available data. This approach has been used to produce notional representations of aircraft and engine models in most weight/passenger classes and thrust levels. With its capabilities, EDS has become the ideal software solution to perform technology infusion studies, develop unconventional propulsion/aircraft systems, and support the establishment of future performance goals.

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